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# PiVOT: Personalized View-Overlays for Tabletops

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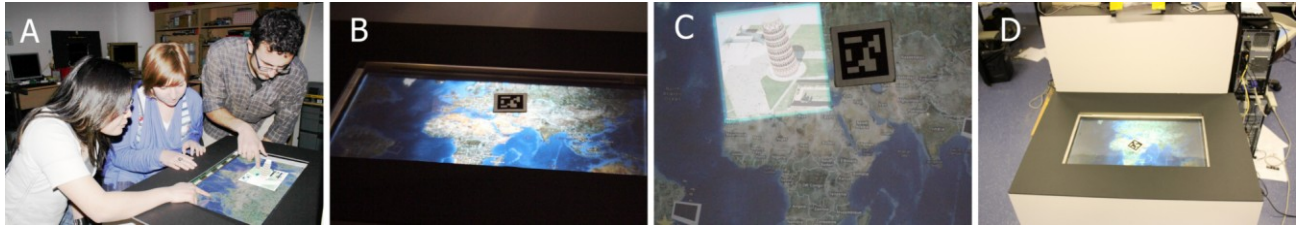


Figure 1: A) One user sees a personalized overlay (*'photoshopped in'* for illustration) which is not visible to the group. The group continues their task unhindered. B) PiVOT in operation; *Shared view* visible to all users. C) *Personal overlay* (visible to one user): A marker placed by user tells PiVOT where to show the overlay. D: PiVOT system.

## ABSTRACT

We present PiVOT, a tabletop system aimed at supporting mixed-focus collaborative tasks. Through two view-zones, PiVOT provides personalized views to individual users while presenting an unaffected and unobstructed shared view to all users. The system supports multiple personalized views which can be present at the same spatial location and yet be only visible to the users it belongs to. The system also allows the creation of personal views that can be either 2D or (auto-stereoscopic) 3D images. We first discuss the motivation and the different implementation principles required for realizing such a system, before exploring different designs able to address the seemingly opposing challenges of shared and personalized views. We then implement and evaluate a sample prototype to validate our design ideas and present a set of sample applications to demonstrate the utility of the system.

## Author Keywords

Multi-view, Lumisty, multi-user, tabletop.

## ACM Classification

H.5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces;

## INTRODUCTION

Digital tabletops have been used to support multiple users to perform collaborative tasks such as planning using maps, CAD applications, or educational tutoring. However, such collaborative applications usually involve a mixture of individual and shared activities, and users often need to tran-

sition between these two activities [21]. In this context, access to personalized views on-demand becomes a necessity in order to support individual activities. Such a situation arises in planning or design tasks where one or more members break off to complete an action, or when some information is available to or restricted to certain users only. For example, in a war-room discussion, shared views can be presented to all participants to provide general awareness of a situation while personalized situational awareness details are presented to specific users only.

The need for individual, or even private tasks, conflicts with the all-sharing nature of tabletops. Individual tasks usually require dedicated use of a small part of the tabletop, which can affect the shared view of the rest of the users [11]. This is in addition to any privacy requirements. From an implementation viewpoint, the default solution is to use mobile/private devices for personalized views and which is at odds with the needs of a collaborative task.

The ideal situation to address these trade-offs would be the one depicted in Figure 1, a collaborative tabletop able to have exclusive and personal views overlaid on top of the *shared view* and able to operate in a *walkup and use* scenario. These *personal views* include *overlays* that allow each user to carry out individual tasks through views which are exclusive to them and thus not visible to the rest of the group. As a result, no user loses context of the group activity and can also perform individual activities concurrently.

We introduce PiVOT (see Figure 1 D) as a solution to these challenges. PiVOT provides two distinct views - a *shared view* (Figure 1 B) and a *personal view* depending on the zone inside which the user is with respect to the tabletop. The *shared view* is visible to all users while the personal view can be customized to contain *personal overlays* visible only to specific users. These overlays (Figure 1 C) can be used to undertake individual tasks. They co-exist on the same surface of the tabletop and do not interfere with the shared view. This is a key contribution of this paper.

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PiVOT uses two display elements in tandem, one to show the *personal views* and the other for the *shared view*. Both elements present information on the same tabletop but their visibility depends on the position (and potentially the identity) of the user. This works because each display acts as a see-through element for the other view. We analyze the principles of operation of these displays and explore different implementation possibilities using suitable see-through elements.

We implement a proof-of-concept prototype that relies on using polarized and unpolarized light sources, modified Liquid Crystal (LC) panels and Lumisty film to present the two non-conflicting views. We finally illustrate the capabilities of the system using several demo applications and evaluate the amount of interference from the *personal view* as perceived by a user of the *shared view*.

The main contributions of this paper are:

- Present a system that displays a *shared view* which is unaffected by collocated *personal overlays*.
- Analyze the operating principles and identify the most promising physical arrangements.
- Implementation of a working prototype to validate our design and evaluate the image quality for *shared* and *personal views*.
- Through a series of example applications demonstrate the capabilities of the implementation.

## RELATED WORK

Group activities around interactive tabletops usually involve *mixed-focus collaboration* (individuals work together and break-off for one-person tasks at regular intervals) [3]. This results in *coupling* between individuals as they transition from one activity to another [21].

Some tools have been proposed to support this kind of collaboration. *Filters* [21] or *transparent overlays* [1] affect the whole tabletop, which encumbers simultaneous shared tasks. *Lenses* or *shadow boxes* [21] only apply to a part of the tabletop, alleviating *interference* [11,16] and enforcing *territoriality* [19,22].

Many of the systems using these tools rely on a single-view tabletop. Thus, all the views and personal *territories* are spatially collocated in the same view and interfere with each other for placement. The availability of personal *territories* is limited by the arrangement and size of other *territories* and *workspace coordination* [18] becomes a necessity. Even though increased size and spatial separation can mitigate these conflicts, single-view tabletops will always be subject to *interference*.

As an alternative, some authors propose digital canvas stitched together with multiple display elements, as an alternative to single-view tabletops. As seen with WeSpace [23] and Geospatial [2] multiple devices can be interconnected to facilitate collaboration with spatial separation between shared and personal view spaces. Other implementations like E-conic [12] and LUMAR [13] integrate

handheld displays with the tabletop. However as discussed by Ryall et al. [16], the increased size or number of screens doesn't necessarily provide additional advantages.

Another approach is using *overlapping views*, i.e. to display several views, collocated on the tabletop space but with minimal or no interference among them. The position of the user or special devices will determine the view that each user will see. Projection-based systems such as SecondLight [4] and Visibility Control System (VCS) [17] allow *filters* and *lenses* [21] to be implemented as tangible overlays. SecondLight uses a switchable diffuser to produce a *shared view*, while projecting contents in users' personal handheld-diffusers. These diffusers, when lying on the table occlude the *shared view*, and their contents are visible to other users. VCS uses polarizing filters to filter content as required, so that the user can see personalized views. However, this possibility is only made available to one user.

The *overlapping views* based on the user's position can be implemented using the view control made possible by Lumisty film [20]. Lumisight [9], Uteriorscape [5], TaPS [10], and Bounsight [14] present different alternatives in which people seated around a table can be shown different views based on their position on the same display surface. These systems divide the space around the tabletop in several regions, so that people can see different contents on the tabletop according to the region they occupy. However as the film acts as single-view diffuser over a fixed view area, two users in the same region cannot get different views. Besides, such diffuser film on its own doesn't support stereoscopic views without additional devices (like HMDs).

Some displays have demonstrated the ability to provide multiple users with auto-stereoscopic views (wherein each eye of the user receives a different perspective of the 3D view, without requiring special devices such as HMDs or shutter glasses). IllusionHole [7], Tabletop Autostereoscopic System (TADS) [24] and MUSTARD [6] allow this by the use of blocking masks and viewing holes and deliver multiple views to individuals based on their spatial position relative to the system.

To summarize, delivering overlapping *personal overlays* which do not interfere with the *shared view* can potentially enhance mixed-focus collaboration but challenging to provide with current tabletop display technology. The implementations which currently do support overlapping views do so with restrictions. Some don't restrict the visibility of views to intended for one user only; others fail to support several users. Moreover, existing designs share a common deficiency: all the views support the same kind of content, let it be 2D or stereo 3D. PiVOT provides personalized non-stitching view overlaps to support these functionalities.

## PIVOT: DESIGN & PRINCIPLES

PiVOT is a collaborative tabletop display that is designed to support mixed-focus collaboration. PiVOT consists of two view-zones: one that provides the *shared view* and a second zone that provides the *personal view* to all users.

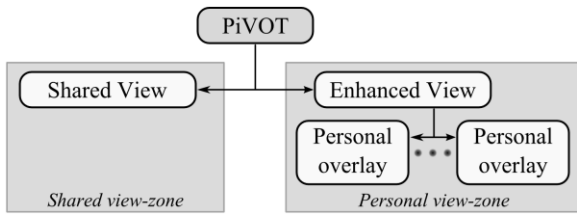


Figure 2: Relationship between different views available in PiVOT.

The relationship between different view-zones and views in PiVOT is illustrated in Figure 2. All users can see the *shared view* at all times but at any moment a user can access his/her *personal view* by changing their position (say for example by leaning forward). This supports the *mixed-focus* collaboration requirement of allowing a user to dynamically transition between individual and group activities by e.g. leaning forward or sitting back. Other users viewing the *shared view* are not affected by the presence of the *personal views* in the same space.

Personal views can either be overlays that are specific to a user or view enhancements that are accessible to any user who enters the personal view-zone. This *enhanced view* carries additional information that individual users may find useful in a collaborative activity but can interfere with the group activity. Any user can access the *enhanced view* by changing their position to enter the personal view-zone.

The personal view-zone can also contain *Personal overlays* which are individual overlays attached to a specific user. This means, any user entering the personal view-zone will not see the *personal overlay* unless it is meant for him/her. At the same time, multiple users can have their *personal overlays* in the same display location. The system manages the presentation of information on the *personal overlay* such that there is minimal interference between the competing content views.

A final unique feature of PiVOT is that the *personal overlays* support *mixed-content* (both 2D and 3D). While one user is viewing auto-stereoscopic 3D content within one overlay, the other user could be viewing 2D content on another overlay. *Mixed-content* also does not affect the requirement that the information meant for one user must be visible only to that user only.

By default, PiVOT operates like a standard tabletop, allowing all users to interact with the *shared view*. In the default mode, all inputs are directed to the *shared view*. But if identity and head-position of the user associated with the input is available then PiVOT also allows users to interact with content in the personal view-zone. The identity and head-position is used to first establish if a user is looking at content in the personal view-zone and if so directs input to that zone. A user positioned in the shared view-zone (and hence not necessarily tracked by PiVOT) can touch the surface where another user's *personal overlay* exists. However PiVOT directs this input to the *shared view* leaving the *personal overlay* unmodified. Only inputs from the

owner of the *personal overlay* can affect the *personal overlay*. This approach allows shared and personal views to be considered as two separated workspaces, containing different contexts that the user can interact with depending on the user's head position.

### PiVOT Components

PiVOT works by operating two displays simultaneously arranged in tandem, one for displaying the *shared view* and another one displaying the *personal view*, containing the *enhanced view* and *personal overlays* of all the users.

The *shared view* has to be visible to any user located in a specific region. This view is independent of how many users are using the system and if they are also accessing *personal overlays* or not. PiVOT also has to use another region to display *personal overlays* where and when required by the users. The display that contains them must not interfere with the operation of the *shared view* and each overlay must only be visible to its associated user.

As the system consists of two display elements that work in tandem for displaying both the views, each display element needs to be selectively transparent or see-through for the content meant for the other display. This core feature of the two elements to be selectively see-through can be achieved in many ways.

### See-through Display Elements

See-through display elements fall into three categories. These are: temporal switching elements; spatial view control elements and polarization dependent elements. Each of these three categories relies on two possible techniques: diffusion or direct display. Diffusion based displays require a projector as their image-source during their operation in diffuser mode or non-see-through mode. Direct displays rely on a light-source but form the image on their own. We briefly discuss each to explore their suitability.

**Temporal switching elements:** SecondLight [4] is a good example of a temporal switching see-through element. Using a switchable LC diffuser synchronized with fast optical shutters, see-through content can be projected when the diffuser is transparent. When the diffuser is switched to its diffuser mode, content is displayed on it. However, with this implementation, the see-through content needs to be viewed by using a handheld diffuser making it visible to all users and occluding their view of the shared content.

**Spatial view control elements:** These elements are see through when viewed from certain positions and are transparent from other angles. The two common examples of this type are Holographic Optical Element (HOE) and Lumistyl film.

**HOE** acts as a diffuser surface for projected information. The advantage of HOE is that multiple views can be generated on the same surface, so it could be used to display the *personal overlays*. It also acts as a see-through element. The trade-off with using HOEs is that each user would require one projector per eye for the overlays.

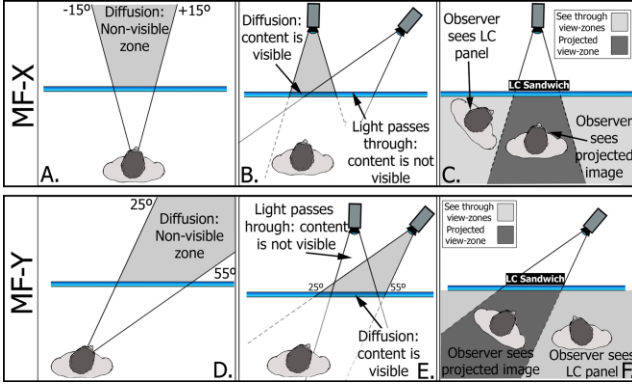


Figure 3: Lumisty film diffuses light at specific angles. Hence objects behind the film are not visible (A, D). The film also acts as a diffuser for projectors (B, F). PiVOT uses both features (C, F): In the *projected view-zone*, observers see the projected image, but not the data on the LC sandwich; the opposite happens in the *see-through view-zone*.

*Lumisty film* as used by Lumisight [9] is a view-control film that diffuses light incident at specific angles. A dual projector solution, as shown with Uteriorscape [5], can hence be used to implement personalized view overlay within the see-through view-zone. A passive tangible overlay made up of the same film can act as the secondary diffuser surface. However as with the switchable diffuser option, once any user is positioned in the view-zone of the second diffuser, only one view is visible. This implies that while Lumisty can serve as the *shared view* display, we need to use a different approach for the *personal view*.

**Polarization dependent elements:** These elements have selective behavior towards polarized light. With VCS [17], the polarized light is blocked using filters. Another system is the LC sandwich arrangement as shown in MUSTARD [6]. That system is capable of acting as a see-through element for unpolarized light and can deal with multiple personalized views using hole-mask patterns sourced by a polarized light source. Each of the personalized views is only visible at the specific location where the user is situated.

An implementation using static patterns as shown in TADS can also present the view overlays along with the shared view. Both MUSTARD and TADS require precise eye-position information to work and tend to degrade in operation as the number of users increases. However, MUSTARD appears a favorable choice because its see-through capability allows a secondary device to display the *shared view*. MUSTARD could simply display the *personal view*, with no degradation in quality due to the number of users that interact with the *shared view*.

It is clear that as a standalone element none of the see-through elements can provide the solution desired. In the next section we describe a solution using Lumisty film as the *shared view* source and a LC sandwich element as the *personal view* source.

## IMPLEMENTATION STRATEGIES

PiVOT brings together a LC sandwich and Lumisty film to present the *shared view* or the *personal view*, according to the location of the user. The LC sandwich displays the *enhanced view* and the *personal overlays*. A projector using Lumisty film as a diffuser presents the *shared view*.

The first two subsections detail the principles that support the correct operation of PiVOT. We first explore the behavior of Lumisty film to produce two non-conflicting collocated views of the table-top. Then we explore the LC sandwich arrangement to support user-specific or personal overlays. In the third subsection we analyze possible strategies to arrange PiVOT's basic components (projector, Lumisty film and LC panels) in order to comply with our requirements.

### Selective workspaces with Lumisty film

Lumisty film diffuses light incident on it at a specific angle. This allows it to be used as a selective projection screen that displays its contents based on the position of the user.

Two types of Lumisty films will be analyzed (MF-X and MF-Y), each of them operating on different angles. MF-X film diffuses light incident on it at angles between  $(-15^\circ, +15^\circ)$  to the normal. MF-Y film diffuses light incident on it at angles between  $(+25^\circ, +55^\circ)$  to the normal. While a third type (MF-Z) exists, we do not discuss its operation in this paper. The film diffuses incoming light in the ranges specified for each film. As a result, an observer will not see any object behind the film in that range (shaded zones in Figure 3 A, D)

This diffusing effect of Lumisty films can also be used for projectors. A projector needs its light to hit a surface and get diffused so that its image becomes visible. As a result, if a projector is positioned so that its light hits the film in the appropriate angle, its contents will become visible to the users. If the projector's light is not incident in the appropriate angle, its light will simply pass through the film and not be visible (see Figure 3 B, E).

However, Lumisty films do not diffuse light in every direction. Observers must be located in a specific area (*projected view-zones* in Figure 3 C, F) to view the image; otherwise, they will not be able to see it (*see-through view-zones* in Figure 3 C, F).

These features have been used in our advantage during the creation of PiVOT to support simultaneous and collocated *shared views* and *personal views*. If a user is in the *projected view-zone*, the user will see the image (i.e. the *shared view*) projected on the Lumisty film. However, if the user is in the *see-through zone* the image from the projector is not visible but he will be able to see the object behind the Lumisty film, that is, the LC sandwich that displays the *personal view* containing the *personal overlays*. Practically, this allows a seated user to switch between these two workspaces by simply leaning forward or sitting back.



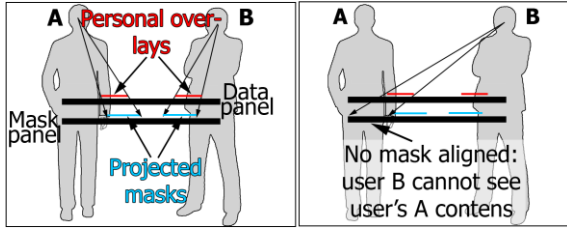


Figure 4: Masks in the data panel align to the personal overlays displayed in the data panel. The position of each user's eyes is used to compute this projection (left). From user B's point of view, there is no mask behind user A's overlay (that region of the mask is black). As a result, user B cannot see user's A contents (right).

### LC sandwich for user-specific Personal Overlays

PiVOT uses a pair of LC screens [6] to display *personal overlays*. There are two key features of the LC sandwich setup that allow it to support the unique requirements of *personal overlays* on PiVOT.

The LC sandwich acts as a see-through element for unpolarized light while using polarized light to display content. To achieve this, a setup as shown in Figure 5 is used. The LC sandwich contains an unmodified LC panel that acts as a source of polarized light. This is called the mask panel. The other panel (data panel) is modified by removing its rear polarizer. With this arrangement, the content displayed on the data panel is only visible if illuminated by polarized light from the mask panel. By displaying special light patterns on the mask panels, we can also control which user sees which part of the data panel (see Figure 4 right). By rapidly switching the patterns, it is possible to deliver different content to different users at the same time, without them seeing content meant for other users. It is also possible to deliver different images to each user's eye, providing support for stereo 3D graphics. The operation of mask pattern and underlying methods to do so are explored in detail in MUSTARD [6].

Finally any unpolarized light (e.g. from a projector) passing through the LC sandwich will not make the content on the data panel visible. At the same time, the content carried by the unpolarized light is also not affected. Thus the LC sandwich is included in PiVOT to:

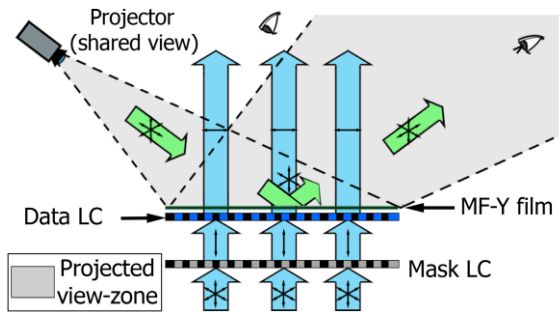


Figure 6: PiVOT Design 1. Projector projecting from above onto MF-Y Lumisty film. The LC sandwich is placed below.

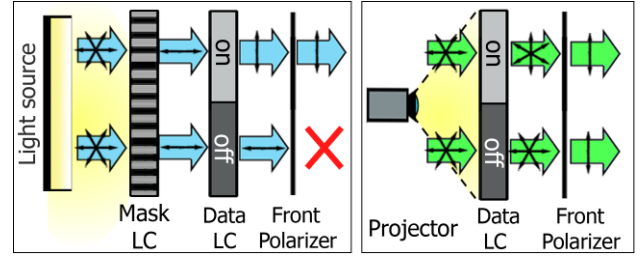


Figure 5: Basic operation of the LC sandwich. The data panel interacts (block/transmit) with polarized light (one axis arrows) coming from the mask panel, according to the information that it wants to display (left). It does not interact with the non-polarized light coming from the projector allowing it to pass through (right).

**Present Personal Views:** The rear panel (mask panel) acts as a source of light that makes it possible to present *Enhanced views* and *Personal Overlays*. Overlays are visible only from the position of its associated user (see Figure 4 left). As the mask is not aligned for the rest of the users they will not be able to see other users' personal overlays (see Figure 4 right). Even in case of conflict (two overlays in the same space), the mask pattern allows conflict resolution so that each user sees their view only.

**Support mixed 2D & 3D content:** This is possible by using different masks. A fully white mask can be used to display text, videos or 2D contents in general. Random Hole (RH) masks [6,24] and vertical parallax barriers (VPB) [15] can also be implemented to provide support for stereo 3D contents. The type of mask can be determined based on content and conflict with other users' masks. The RH mask is the default fallback in presence of conflict as it (using conflict functions [6]) can display each user's *personal overlay* with minimal interference from other overlays.

**Be transparent to the shared view:** The LC sandwich does not disrupt the operation of the projector on the Lumisty film. This is true even if this image is projected through the data panel of the sandwich. As shown in Figure 5 left, the data panel can be used to prevent horizontally polarized light coming from the mask panel to be presented to the user. However, the light coming from the projector is not polarized (see Figure 5 right). As a result, the data panel will remove the part of the light of the projector that is horizontally polarized, but most of the light will still pass through and reach the Lumisty film on the other side.

### Possible Arrangements

There are several potential arrangements of the LC-sandwich, the projector and the Lumisty film to support operation of PiVOT. We identify and analyze some of these arrangements here.

**1. Top Projection Using Reflection:** In this arrangement the projector is placed on top of the table at an angle to hit the MF-Y Lumisty film at its blocking angle. It displays the *shared view* and its image is visible in the *projected view-zone* (see Figure 6). The LC sandwich operates independently, below the Lumisty film and displays the person-

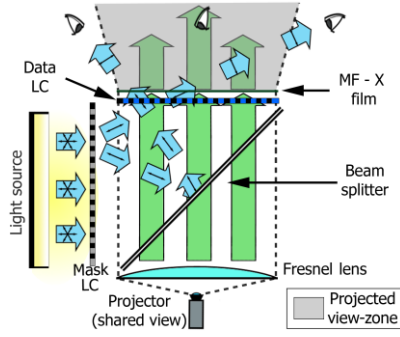


Figure 7: PiVOT Design 2. The projector-Fresnel setup projects the shared view onto the MF-X Lumisty film. Beam-splitter allows overlays to be visible from both sides of the tabletop surface.

al view. The main benefit of this arrangement is its simplicity, but it fails to provide a good quality for the *shared view*. Lumisty film reflects only ~15% of the light at its blocking angle. Thus a high power projector is required to achieve satisfactory brightness and contrast. Besides, overhead projectors can cause hand-occlusions and cast shadows in a collaborative setting.

**2. Beam-splitter with Fresnel lens:** This arrangement uses a MF-X Lumisty film and a projector pointing at the tabletop from below displaying the *shared view*. The data panel is located right under the Lumisty film and the mask panel is placed perpendicular to them (see Figure 7). The *projected view-zone* of this setting lies above the tabletop and *see-through view-zones* are available on both sides of the tabletop. A beam-splitter is added to the setup to allow visibility of the personal views from both sides. As shown in Figure 7, on one side, the personal view is in direct line of sight from the user to the mask panel. On the other side the user reflection of the mask panel on the beam-splitter is used.

The projector uses a Fresnel lens to reduce the size of the setting. Having the light hit the Lumisty film in the range of  $(-15^{\circ}, +15^{\circ})$  would force a projector covering a table of one meter wide to be placed at 1.86 meters below the tabletop. The Fresnel lens removes this limitations, ensures all beams to pass through the beam splitter at the same angle (to avoid distortion) and hit the Lumisty film at its optimal angle for diffusion. However, the size of the beam-splitter

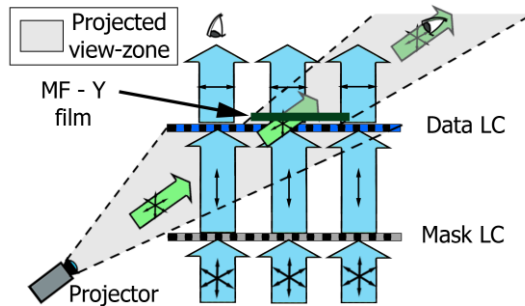


Figure 9: PiVOT Design 4. The overlay as a passive element. MF-Y Lumisty film used to view an overlay while the LC sandwich presents shared view above the tabletop.

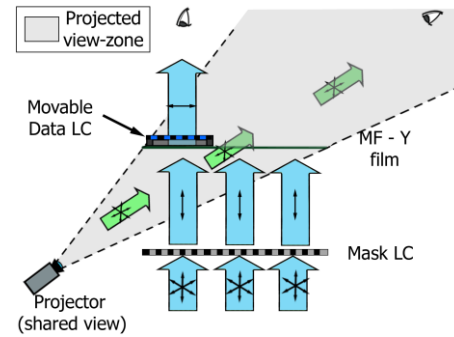


Figure 8: PiVOT Design 3. The overlay as an active element. MF-Y Lumisty film is between the movable LCD data panel and the mask panel of the LC sandwich.

must be equal to the size of the tabletop. This leads to a problem with scalability of this design as a large beam-splitter is not easily available.

**3. Active tangible overlay:** This arrangement has similarities with LUMAR [13] which uses a small handheld placed on the table to show additional views. The arrangement uses a MX-Y Lumisty film and a short-throw projector to present the *shared view*. The mask panel is located at a fixed distance under the Lumisty film. As a major difference, this setting uses a small LCD panel as an active tangible overlay as seen in Figure 8. This LCD panel is modified to act as the data panel part of the LC sandwich but can be moved and positioned as desired. When placed on the tabletop, data on the panel becomes visible when light from the mask panel passes through it.

However, since the small LCD panel allows the diffuse unpolarized light from the *shared view* to pass through unaffected, the *personal overlay* is only visible to the owner of the overlay. At the same time, other users can continue seeing the *shared view* at the same spot where the overlay rests, even though some distortion can exist. Another benefit of this setting is that the native resolution of the movable LCD panel can be used to display the personal overlay, while other settings only use a relatively small part of the resolution of their data panels.

**4. Passive tangible overlay:** In contrast to the rest of the arrangements, this uses the LC sandwich to present the *shared view*. These contents are visible from above the

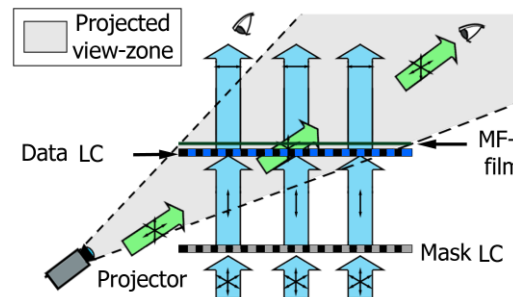


Figure 10: PiVOT Design 5. Projector projecting from below onto MF-Y Lumisty film. The LC sandwich is placed below the film and the overlays are visible from above the tabletop.

tabletop (see *see-through view-zone* in Figure 9). A projector is then used to display *personal overlays* onto small movable patches of MX-Y Lumisty film, which are visible from the size. This setup is advantageous when the tasks involved in the *shared view* require stereoscopic 3D contents, while personal tasks have a preference for 2D contents. In this context, the LC sandwich can be used to render stereo 3D contents for all the users (i.e. using hole masks, as described in [6,24]), while 2D contents can be projected on patches of Lumisty film.

**5. Rear Projection Using Diffusion:** This arrangement, shown Figure 10, is an alternate form of the passive tangible overlay with some differences. Instead of using Lumisty patch, the whole tabletop is covered with the film. The *shared view* can therefore be presented on the film and the overlays are generated by the LC sandwich. The *shared view* is now limited to 2D content but the overlays can display both 2D and 3D contents. This arrangement leads to a compact design of the tabletop, and its hardware requirements are minimal.

### PIVOT PROTOTYPE IMPLEMENTATION

We explored creating a prototype based on the *Active Tangible Overlay* design but we quickly realized that the operation of this prototype didn't work as expected, due to the arrangement of the display elements. Although Lumisty acts as a see-through element it affects the polarization of the light passing through it. So light from the mask panel loses its polarization after passing through the Lumisty film thus destroying the functioning of the LC sandwich. Our working prototype of PiVOT is based on the *Rear projection with Diffusion* design (Design 5) as it offered the greatest flexibility in operation and can be implemented by modifying off-the-shelf components.

The hardware prototype of PiVOT consisted of an LC Sandwich for creating personal view and a projected display for the *shared view* (see Figure 11). For the personal view we used two modified LG IPS2321P 23", 1980x1080 LCD monitors to build the LC sandwich. The LC panels

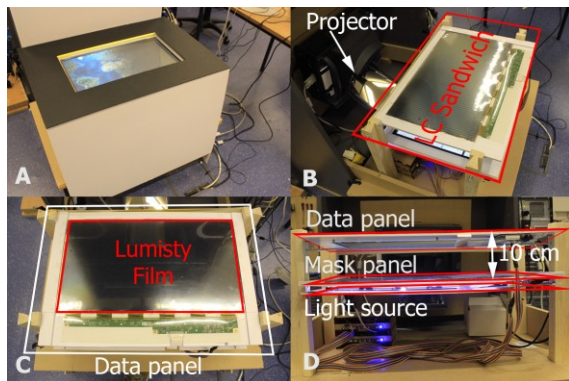


Figure 11: Overview of the project implemented: (a) External appearance; (b) general view of the projector and the LC sandwich; Lumisty film is applied on the data panel (c), the mask panel and the diffuser are located below the data panel at a distance of 10 centimeters.

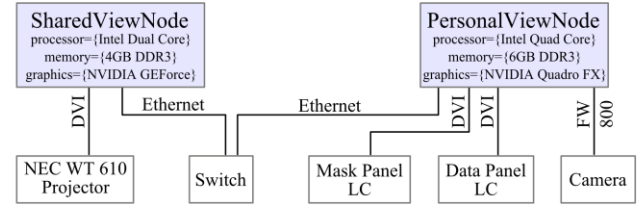


Figure 12: System Architecture for PiVOT.

were dismantled from their frames and the rear polarizer was removed from one LC to use it as the data panel. Both panels were mounted parallel to each other with a separation of 10 cm on a custom frame. The light source and diffuser that comes with the IPS2321P monitor were used as the source of diffused light for our LC sandwich.

The *shared view* was implemented by using a NEC WT610 short-throw projector mounted and adjusted so that it could project its image through the 10 centimeter gap between the two LC panels. Lumisty MX-Y film was stuck to the top LC panel and used as the diffusion surface for the image coming from the projector.

PiVOT requires using a 3D tracking system to determine the position of both the *personal overlays* and the user's eyes. In this prototype, the tracking subsystem was implemented on top of ARToolKitPlus, using a Grasshopper Express GX-FW-10K3M-C Firewire camera working at a resolution of 1024x768 and at 60 fps. The user's heads were tracked using ARToolKitPlus markers worn by the users. The eye positions were estimated using a fixed offset from the markers. The system also tracked tangible fiducial markers and single finger touches to interact with the tabletop. The complete system architecture is described in Figure 12.

A software framework was created to support the creation of applications for the tabletop, supporting three modes of operation: monocular, VPB and RH masks. The first mode works well with 2D contents and non-stereo motion parallax 3D contents. The second and third modes are used to generate stereo 3D contents. Ogre 3D was used as the rendering engine to generate the 3D contents, the masks and to compute the required mask projections. NVidia Cg programs were used to merge the 3D contents and their masks and to run the conflict resolution functions (see [6]). OSC commands on top of UDP were used to synchronize both computers. *PersonalViewNode* acted as a server, running the logic of the application and the subsystems that allowed it to generate the *personal overlays*. *SharedViewNode* acted as a slave, containing a local copy of the contents to display and reacting to the OSC commands received.

### EXAMPLE APPLICATIONS

Two test bed applications have been implemented to illustrate the capabilities of the system.

The first one is a geospatial exploration application using Google maps that is inspired by the Multi-user geospatial system from Forlines et al [2]. Our application provides a



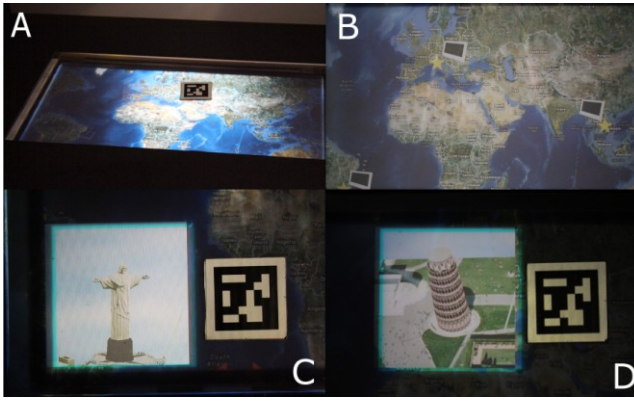


Figure 13: Map application on PiVOT. (A) *Shared view* (B) *Personal overlay* zone with additional information. (C) & (D) Two *personal overlays* showing 3D content.

*shared view* that allows users to visualize and explore maps (see Figure 13 A). When users lean-forward they get access to an *enhanced view* that is visible inside the personal view-zone and that shows flags on important world landmarks. In this way users know about the availability of important additional information.

The icons in Figure 13 B indicate these locations which include landmarks like the city of Pisa in Italy and Sydney in Australia. This *enhanced view* information is not available in the *shared view*, but available to any user who leans forward to enter the personal view-zone. Once inside the personal view-zone, users can place a tangible marker on map spots to create a *personal overlay* and explore the monuments, by moving the marker or moving themselves (see Figure 13 C, D). These marker-based *personal overlays* are personal to the user placing the tag. Markers are tied to specific users who are also tracked by the system and when the user moves, the *personal overlay* is updated so a perspective corrected 3D rendering of the building is displayed. Furthermore, any other user leaning forward at a different location will *not* see this personal overlay but will instead continue to see the *enhanced view*. We are able to manage the visibility of *personal overlays* by using a Random Hole mask at the location of the marker in mask panels of the LC sandwich.

The second application is from an educational context and meant to teach human anatomy (see Figure 14). The *shared view* allows users to explore a 3D model of a human body (see Figure 14 A). The *enhanced view* which is accessed by leaning forward contains information about the organs that can be examined with a *personal overlay*. Users can access the extra information both by placing fiducial markers on the icon or by touching them with their fingers (see Figure 14 C). In these *personal overlays* users can look at *medical reports* which can contain text, videos or other kinds of information (see Figure 14 D). Organs are displayed using 3D models. The different techniques to display 3D contents (monocular, VPB and RH mask) are available.

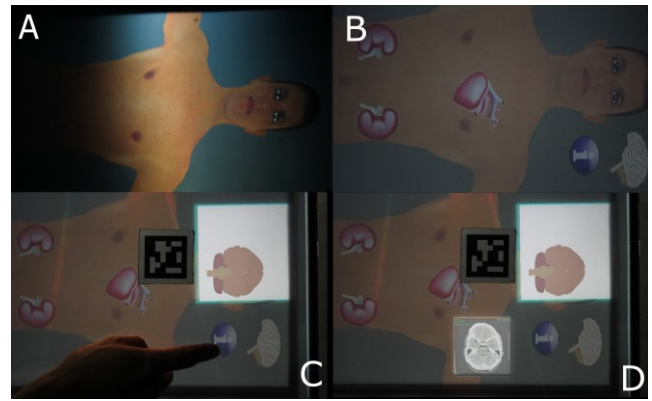


Figure 14: Anatomy application on PiVOT. (A) *Shared view* (B) *Personal view* showing location of additional content. (C) User with access to one *personal overlay* about to trigger one more. (D) User with access to two *mixed-content* (2D and 3D) *personal overlays*.

## EVALUATION

There are two ways in which *personal overlays* may cause interference. First, the *personal overlays* can cause interference with the *shared view*. This interference is what PiVOT proposes to solve.

Second, *personal overlays* can interfere with each other when they are collocated in the same display area. This interference is visually relevant to the LC sandwich only. The LC sandwich approach described in MUSTARD [6] details the use of RH masks and underlying pixel conflict functions to resolve this interference. A detailed evaluation of interference and image quality of views has been performed for MUSTARD [6]. Their results and conclusion are also applicable to PiVOT's LC sandwich, so we do not repeat the study.

We however, carry out a system evaluation to examine the interference caused by the *personal overlays* on the *shared view* for PiVOT.

### Metrics

We evaluate using two metrics: Peak Signal to Noise Ratio (PSNR) and the Quality Mean Opinion Score ( $Q_{MOS}$ ) from Mantuik's HDR-VDP2 [8]. PSNR measures how much noise (from the overlay) is present in the shared view.  $Q_{MOS}$  quantifies the interference from the overlays as perceived by human eyes.

### Setup

Both metrics use a reference image and a test image for comparison. Two positions that simulated the users sitting around the tabletop were selected to create the images. At each position, the users' eyes were 80 cm from the center of the tabletop. The first position placed the projection center-line, the center of the tabletop and the user's eyes in the same plane.

The second position simulated that of a user sitting next to the first user. We use the PiVOT implementation described earlier to show the images. A Canon 550D camera, placed at the eye positions, was used to capture the images. The

zoom was set to maximize the coverage of the tabletop and photographs were taken at f/8; 1/30s; ISO-1600.

### Procedure

We evaluate 5 scenarios of operation, three of these depict scenarios with maximum possible interference from the overlays and two are of the system in normal operation. The different content on the LC sandwich are: black background (B in Figure 15), white background (W), black & white pinstripes (Pin), map application showing *shared view* and an *enhanced view* in the LC panels (SV) and finally map application as before but with an additional *personal overlay*.

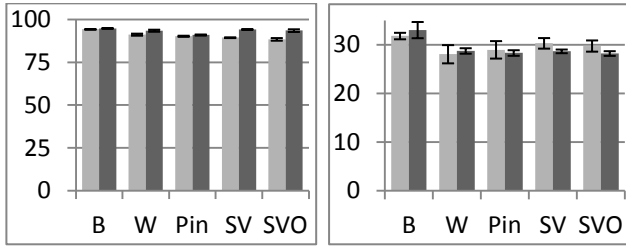


Figure 15: Image quality scores for each position. Q<sub>MOS</sub> (left) and PSNR (right). Shared View (SV) and Shared View with Overlay (SV+O) depict normal operation mode.

For each position, the reference image was taken with the LC sandwich panels off while the *shared view* from the map application was projected on the Lumisty film. Five test images were captured for each position and each scenario (25 test images per position), with the panels turned on and the *shared view* being shown on the Lumisty film.

### Results

Q<sub>MOS</sub> scores were computed using the reference implementation (version 2.1). The highest possible Q<sub>MOS</sub> score is 100 and means no difference in the test and reference images. As can be seen from Figure 15 (Left) the Q<sub>MOS</sub> values in our evaluation are close to 100, implying there is almost no difference between the reference image and the test image. The lowest score obtained was 88.85 for shared view (SV) and SV with overlay (SV+O) were between 88.85 and 94.41. The PSNR scores for all conditions show a similar trend to the Q<sub>MOS</sub> values. We can infer that the interference from the overlays is low enough for our concept to work.

### DISCUSSION

Our evaluation used a range of interfering images in the personal overlays that were designed to explicitly highlight any leakage of *personal overlays* onto the *shared view*. Our results show that there is very little interference and that it is independent of the nature of the content shown in the *personal overlay*. This means that the PiVOT concept works and opens new possibilities in collaborative tabletop that supports mixed-focus collaboration and a wide range of 2D and 3D content in the *personal overlays*.

PiVOT provides the possibility to co-locate two distinct workspaces, shared and personalized, and by tracking the position of each user, the system can know the workspace

he/she is viewing. As a result, their interactions (touch inputs, gestures, voice commands) can be interpreted in the appropriate context.

Another relevant capability of PiVOT is its support for *mixed-content*, which offers users the ability to switch between different types of 3D and 2D data and therefore supports a greater number of applications. To date most tabletop systems either support interactive exploration of 2D or 3D content but rarely allow users to dynamically switch between the two of them. However in many applications it is often useful for users to constantly switch between the two types of content. PiVOT provides this flexibility by using the LC sandwich to create the *personal overlays*.

Finally, the distribution of the workspaces that PiVOT uses can change, to adapt to different interaction styles and user preferences. Some usage scenarios will require users to access the *shared view* when they gather above the tabletop (i.e. walk up and use applications) while *personal overlays* are better accessed when sitting back. Others will need a *shared view* to be available to users when they are sitting around the table-top (e.g. meetings). Although our implementation of PiVOT used a specific arrangement of the workspaces it can be easily adapted to support other arrangements. From a range of identified possible designs, we implemented the PiVOT prototype based on the most compact design with the least hardware requirements (Design 5). While this prototype validates our concepts, it is flexible to further adaptations. With minor modifications to the software, it can operate like Design 4 wherein the position of the shared view and the personal views are interchanged. By adding another projector and additional layers of Lumisty film, the table can become accessible from all four sides instead of the current three sides.

Future research can look at the various interaction issues such as how users might move content between the shared and personal views without disrupting group activity or how interactions with PiVOT might affect group awareness and coordination.

### CONCLUSION

This paper presents PiVOT, a system that supports mixed-focus collaboration through the use of a Lumisty film, a standard projector and a modified Liquid Crystal in a tandem configuration. The standard projector provides a *shared view* that is visible to all users while the Lumisty film combined with the LCs provide a personal view that support individual work. By moving in and out of the view-zones the user can switch between individual work and group work. PiVOT also supports the use of different types of content such as 2D images, text, auto-stereoscopic 3D and multi-view images in the personal view. Through a system evaluation we show that there is very low interference from the personal overlays on the shared view demonstrating that the PiVOT prototype and concept work.

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